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Decaying Hidden Gaugino as a Source of PAMELA/ATIC Anomalies

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Abstract

We study a scenario that a $U(1)$ hidden gaugino constitutes the dark matter in the Universe and decays into a lepton and slepton pair through a mixing with a $U(1)_{B-L}$ gaugino. We find that the dark-matter decay can account for the recent PAMELA and ATIC anomalies in the cosmic-ray positrons and electrons without an overproduction of antiprotons.

1 Introduction

In the string landscape of vacua, the presence of many gauge symmetries besides the standard-model (SM) gauge groups is a quite common phenomenon. Therefore, it is very interesting to consider not only low-energy supersymmetry (SUSY) but also additional low-energy gauge symmetries.

If some of the extra $U(1)$'s are unbroken, the corresponding gauginos may receive SUSY-breaking soft masses of the order of the gravitino mass, $m_{3/2} \simeq O(1)$ TeV. If those $U(1)$'s are confined on one brane far separated from another brane on which the SUSY SM (SSM) particles live, direct couplings between the $U(1)$ gauge multiplets and the SSM particles would be exponentially suppressed [1]. Then the gauginos of the extra $U(1)$'s may have lifetimes much longer than the age of the Universe, and therefore can be candidates for dark matter (DM) in the Universe. We call such gauginos as hidden gauginos and consider a scenario that they constitute the DM [2].

The purpose of this paper is to show that the decays of the hidden gauginos naturally explain anomalous excesses in the cosmic-ray electron/positron fluxes observed by PAMELA [3] and ATIC [4]. As we will see in the following sections, the decay proceeds through a mixing with the $U(1)_{B-L}$ gaugino.¹ The hidden gaugino decays into a lepton and slepton pair, and the slepton will further decay into a lepton and a neutralino. Those energetic leptons from the DM decay are the source of the PAMELA/ATIC anomalies.

The PAMELA experiment also reported the antiproton/proton ratio, which provides a severe constraint on the DM contribution to the antiproton flux [6]. It is quite remarkable that the present model is free from an overproduction of the antiproton, if the decay into a quark and squark pair is kinematically forbidden [7]. (See Refs. [8, 9, 1, 10, 11] for other ways to avoid the problem of the antiprotons.) Our model predicts a bump at several hundred GeV in the diffuse gamma-ray flux, which may be tested by Fermi Gamma-ray Space Telescope [12] in operation. Also, since the mass scale of the SSM particles is not directly related to the energy scale of the electron/positron excesses, the gluino mass can be lighter than e.g. 1 TeV, and hence SUSY may be discovered at LHC.

¹ See Refs. [5, 1] for the non-supersymmetric counterpart.

2 Model and decay of hidden gaugino

To demonstrate our point we consider a reduced model in $(4+1)$ dimensional space time. The extra dimension is assumed to be compactified on S^1/Z_2 which has two distinct boundaries. Suppose that a hidden $U(1)$ gauge multiplet (λ_H, A_H, D_H) is confined on one boundary and the SSM multiplets on the other. In such a set-up, direct interactions between the two sectors are suppressed by a factor of $\exp(-M_*L)$, where M_* is the five-dimensional Planck scale and L denotes the size of the extra dimension. For e.g. $M_*L \sim 10^2$, the direct couplings are so suppressed that the hidden gaugino will be practically stable in a cosmological time scale [1].²

We introduce a $U(1)_{B-L}$ gauge multiplet $(\lambda_{B-L}, A_{B-L}, D_{B-L})$ and a SUSY breaking multiplet Z in the bulk. The multiplet Z is assumed to have a SUSY-breaking F-term, $|F_Z| = \sqrt{3}m_{3/2}M_P$, where $M_P \simeq 2.4 \times 10^{18}$ GeV. As we will see below, the presence of the $U(1)_{B-L}$ in the bulk enables the hidden $U(1)$ gaugino to decay into the SSM particles through an unsuppressed kinetic mixing between the two $U(1)$'s.

In order to ensure the anomaly cancellation of $U(1)_{B-L}$, it is necessary to introduce three generations of right-handed neutrinos N . The seesaw mechanism [13] for neutrino mass generation suggests the Majorana mass of the (heaviest) right-handed neutrino at about the GUT scale. Such a large Majorana mass can be naturally provided if the $U(1)_{B-L}$ symmetry is spontaneously broken at a scale around 10^{16} GeV. To be explicit, let us introduce two supermultiplets $\Phi(2)$ and $\bar{\Phi}(-2)$, where the $B-L$ charges are shown in the parentheses. In order to induce the $B-L$ breaking, we consider the superpotential,

$$W = X(\Phi\bar{\Phi} - v_{B-L}^2), \quad (1)$$

where X is a gauge-singlet multiplet and v_{B-L} represents the $B-L$ breaking scale. In the vacuum Φ and $\bar{\Phi}$ acquire non-vanishing expectation values: $\langle\Phi\rangle = \langle\bar{\Phi}\rangle = v_{B-L}$, and the $U(1)_{B-L}$ is spontaneously broken. As a result, the gauge boson as well as the gaugino acquire a mass of $M \equiv 4g_{B-L}v_{B-L}$, where g_{B-L} denotes the $U(1)_{B-L}$ gauge coupling. In particular, the gaugino λ_{B-L} forms a Dirac mass term with $\Psi \equiv (\chi_\Phi - \chi_{\bar{\Phi}})/\sqrt{2}$, where χ_Φ

² With our choice of $L \sim 10^2/M_*$, the five dimensional Planck scale M_* is roughly equal to $M_P/10 \simeq 10^{17}$ GeV which is larger than the grand unification theory (GUT) scale ($\sim 10^{16}$ GeV), and the subsequent analysis in the text is valid.

and $\chi_{\bar{\Phi}}$ are the fermionic components of Φ and $\bar{\Phi}$, respectively.

Let us estimate the mixing between the hidden $U(1)$ and $U(1)_{B-L}$ multiplets. The kinetic terms are given by

$$\begin{aligned}\mathcal{L}_K &= \frac{1}{4} \int d^2\theta (W_H W_H + W_{B-L} W_{B-L} + 2\kappa W_H W_{B-L}) + \text{h.c.}, \\ &\supset -i \left(\bar{\lambda}_H \bar{\sigma}^\mu \partial_\mu \lambda_H + \bar{\lambda}_{B-L} \bar{\sigma}^\mu \partial_\mu \lambda_{B-L} + \kappa \bar{\lambda}_H \bar{\sigma}^\mu \partial_\mu \lambda_{B-L} + \kappa \bar{\lambda}_{B-L} \bar{\sigma}^\mu \partial_\mu \lambda_H \right),\end{aligned}\quad (2)$$

where κ is a kinetic mixing parameter of $O(0.1)$, and we have extracted relevant terms in the second equality. On the other hand, the mass terms are given by

$$\mathcal{L}_M = -\frac{1}{2} m \lambda_H \lambda_H - M \lambda_{B-L} \Psi + \text{h.c.}, \quad (3)$$

where we have assumed that the hidden gaugino λ_H acquires a Majorana mass m through the SUSY breaking effect.³ (Note that we assume that the hidden $U(1)$ remains unbroken in the low energy.) We assume that m is of the order of the weak scale, while M is around the GUT scale $\sim 10^{16}$ GeV. The canonically normalized mass eigenstates $(\lambda_1, \lambda_2, \lambda_3)$ have masses $\approx m, M/\sqrt{1-\kappa^2}, -M/\sqrt{1-\kappa^2}$. They are related with the gauge eigenstates $(\lambda_H, \lambda_{B-L}, \Psi)$ as,⁴

$$\begin{pmatrix} \lambda_1 \\ \lambda_2 \\ \lambda_3 \end{pmatrix} \simeq \begin{pmatrix} 1 & \kappa & \frac{\kappa m}{M} \\ -\frac{\kappa m}{\sqrt{2}M} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ -\frac{\kappa m}{\sqrt{2}M} & -\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix} \begin{pmatrix} \lambda_H \\ \lambda_{B-L} \\ \Psi \end{pmatrix}, \quad (4)$$

or equivalently,

$$\begin{pmatrix} \lambda_H \\ \lambda_{B-L} \\ \Psi \end{pmatrix} \simeq \begin{pmatrix} 1 & -\frac{\kappa}{\sqrt{2}} & \frac{\kappa}{\sqrt{2}} \\ \frac{\kappa m^2}{M^2} & \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \\ \frac{\kappa m}{M} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix} \begin{pmatrix} \lambda_1 \\ \lambda_2 \\ \lambda_3 \end{pmatrix}, \quad (5)$$

where we have approximated $m \ll M$ and $\kappa \lesssim 0.1$. The lightest fermion λ_1 is almost the same state as λ_H and is the candidate for the DM.

Using the relation (5) we can derive the interaction between λ_1 and the SSM particles. The λ_{B-L} has interactions with the SSM particles via the $U(1)_{B-L}$ gauge symmetry;

$$-\sqrt{2} g_{B-L} Y_\psi \lambda_{B-L} \phi_{\text{SSM}}^* \psi_{\text{SSM}} + \text{h.c.}, \quad (6)$$

³ The λ_{B-L} may also acquire a Majorana mass of $O(m)$ from the SUSY breaking effect. Including the mass does not change the following arguments.

⁴ A similar mixing could arise from an interaction $\int d^2\theta Z W_H W_{B-L}/M_P$. For $m_{3/2} \sim m$, the resultant mixing angle is of the same order of magnitude as that in the text.

where ψ is the SM fermion, ϕ is its scalar partner and Y_ψ is their (B-L) number. Through the mixing shown in Eq. (5), the λ_1 gets the interaction with the SSM particles as

$$\mathcal{L}_{\text{int}} = -\sqrt{2}g_{\text{B-L}}Y_\psi\kappa\left(\frac{m}{M}\right)^2\lambda_1\phi_{\text{SSM}}^*\psi_{\text{SSM}} + \text{h.c.}, \quad (7)$$

which enables the λ_1 to decay into SSM particles. Its lifetime is estimated to be

$$\Gamma_{\text{DM}}^{-1}(\text{DM} \rightarrow \phi + \psi) \simeq 2 \times 10^{26} \text{ sec } g_{\text{B-L}}^{-2} Y_\psi^{-2} \kappa^{-2} \left(1 - \frac{m_\phi}{m_{\text{DM}}}\right)^{-2} \left(\frac{m}{1 \text{ TeV}}\right)^{-5} \left(\frac{M}{10^{16} \text{ GeV}}\right)^4 \frac{1}{C_\psi}, \quad (8)$$

where C_ψ is a color factor of ψ , i.e., 3 for quarks and 1 for leptons. It is quite remarkable that the hierarchy between the $B-L$ breaking scale $\sim 10^{16}$ GeV and the SUSY breaking mass of the hidden gaugino of $O(1)$ TeV naturally leads to the lifetime of $O(10^{26})$ second that is needed to account for the positron excess.

From Eq. (5) we can see that the mixing of λ_1 with Ψ is much larger than that with $\lambda_{\text{B-L}}$. Thus we need to make sure that the coupling of Ψ to the SSM particles must be small enough. The most dangerous coupling is that with the Higgs multiplets,

$$W = \frac{c}{M_*} \Phi \bar{\Phi} H_1 H_2, \quad (9)$$

where c is a numerical coefficient. If c is of order unity, this operator induces a too fast decay of λ_1 to become DM, since Φ and $\bar{\Phi}$ acquire large expectation values, $\langle \Phi \rangle = \langle \bar{\Phi} \rangle = v_{\text{B-L}} = O(0.1) M_*$. However, we can suppress the above interaction by assigning the R -charges as $R[\Phi \bar{\Phi}] = R[H_1 H_2] = 0$. If the R -symmetry is dominantly broken by the constant term in the superpotential, the coefficient c is expected to be of $O(m_{3/2} M_P^2 / M_*^3)$, and such a coupling becomes irrelevant.⁵

Lastly we emphasize that the longevity of the λ_1 DM arises from the geometrical separation and the hierarchy between M and m , not from conservation of some discrete symmetry such as the R -parity. In fact, we assume that in our scenario the lightest neutralino is the lightest SUSY particle (LSP) and it is absolutely stable with the conserved R -parity. Therefore, in our set-up, there are actually two DM candidates, λ_1 and the neutralino LSP. We assume that λ_1 is the dominant component of the DM for the moment, and will mention such a case that the λ_1 is subdominant in Sec. 4

⁵ There can be an operator, $W = (\Phi \bar{\Phi}) T Q H_2 / M_*^2$, where T and Q denote the right-handed quark and left-handed quark doublet in the third generation, respectively. The decay rate through this operator is suppressed by $O(10^{-2} v_{\text{B-L}}^2 M^2 / M_*^4)$, compared to that into a lepton and slepton pair, and therefore, does not change our arguments.

3 Electron and positron excesses from the decaying hidden-gaugino DM

As we have shown in the last section, the λ_1 is almost stable but has some decay modes through a small mixing with the λ_{B-L} . If the DM is heavier than the sleptons, the DM can decay into slepton + lepton and this slepton causes the SUSY cascade decay and reaches the LSP, emitting high energy SM particles. In the case of the slepton NLSP, the slepton emits only SM leptons. The anomalies observed in the recent e^\pm cosmic-ray experiments can be explained by the energetic leptons from this DM decay. In addition, if the DM mass m is lighter than the mass of squarks, the DM causes almost no hadronic decay which would produce many antiprotons and photons [7].⁶

Now let us estimate the cosmic ray signals from the DM decay. To estimate the energy spectrum of the decay products of the DM, we have used the program PYTHIA [15]. The particles produced in the DM decays are influenced by various factors in the propagation. For the propagation in the Galaxy, we adopt the method discussed in Refs. [16, 17] with the Navarro, Frenk and White halo profile [18];

$$\rho_{DM} = \frac{\rho_0}{(r/r_c)[1 + (r/r_c)]^2}, \quad (10)$$

where $\rho_0 = 0.26 \text{ GeVcm}^{-3}$ and $r_c = 20 \text{ kpc}$. As a diffusion model for the electron and positron cosmic rays, we use the MED model in Ref. [19]. As for the gamma ray signal, we have averaged the halo signal over the whole sky excluding the region within $\pm 10^\circ$ around the Galactic plane. For the extragalactic component, the gamma ray is influenced by the red-shift. We estimate the extragalactic component by using the following cosmological parameters; $\Omega_\Psi h^2 \simeq 0.11$, $\Omega_{\text{matter}} h^2 \simeq 0.13$, $\Omega_\Lambda \simeq 0.74$, $\rho_c \simeq 1.0537 \times 10^{-5} h^2 \text{ GeVcm}^{-3}$, $h \simeq 0.72$ [20].

We set the DM mass equal to 1300 GeV with lifetime $8 \times 10^{25} \text{ sec}$. As for the SSM spectrum, we assume that the LSP is the bino-like neutralino of a mass 148 GeV and the NLSPs are selectron, smuon, and stau with a mass 150 GeV. Note that, with our choice

⁶This assumption seems to be natural, because usual SUSY breaking model indicate that the squarks are much heavier than (right-handed) slepton. In addition, the SM-like lightest higgs mass bound ($m_{h^0} > 114.4 \text{ GeV}$ [14]) also indicate heavy squarks ($\gtrsim 1 \text{ TeV}$.) (The mass of SM-like higgs receives a radiative correction from quark-squark loop diagrams.)

of the mass parameters, thermal relic abundance of the neutralino LSP is suppressed due to efficient co-annihilation; this is to make sure that the neutralino LSP abundance is negligibly small compared to that of λ_1 . (As for the production of λ_1 , see the next section.) For simplicity, we assume that the other SM scalar partners are heavier than the λ_1 and that the λ_1 decays only into the slepton + lepton. In Fig. 1, we show the cosmic ray signals. As for the electron and positron background, we have used the estimation given in Refs. [26, 27], with a normalization factor $k_{\text{bg}} = 0.7$. We have taken into consideration the solar modulation effect in the current solar cycle [27]. We set the gamma ray background flux as $5.18 \times 10^{-7} (E/1 \text{ GeV})^{-2.499} \text{ GeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ as in Ref. [28]. We have assumed the energy resolution is 15% for the gamma-ray signal. As for electron and positron signal, this model can explain the cosmic ray anomalies quite well. The gamma ray signal is not in conflict with the currently available experimental data. Furthermore, our model predicts a bump around several hundred GeV in the diffuse gamma-ray spectrum. Such a feature in the gamma-ray spectrum can be tested by the Fermi satellite [12] in operation.

4 Discussion and conclusions

Let us here discuss the production mechanisms of the hidden gaugino, λ_1 , in the early universe. As we have seen in the previous sections, the interactions of the λ_1 with the SSM particles are extremely suppressed due to both the geometrical separation and a large hierarchy between M and m . In order to produce a right amount of the λ_1 DM from particle scatterings in thermal plasma, the reheating temperature after inflation has to be close to the $B - L$ breaking scale. Such a high reheating temperature is in conflict with the constraint from the notorious gravitino problem [29].⁷ It is therefore difficult to produce λ_1 by thermal scatterings. Nevertheless, the right abundance of the hidden gaugino can be non-thermally produced by the inflaton decay, if the inflaton has a direct coupling to the hidden gauge sector.

The gravitino decay is another possible way to produce λ_1 . Due to the number of

⁷ Note that the gravitino must be heavier than the hidden gaugino, since the hidden gaugino will decay into the gravitino and the hidden gauge boson with a much shorter lifetime, otherwise.

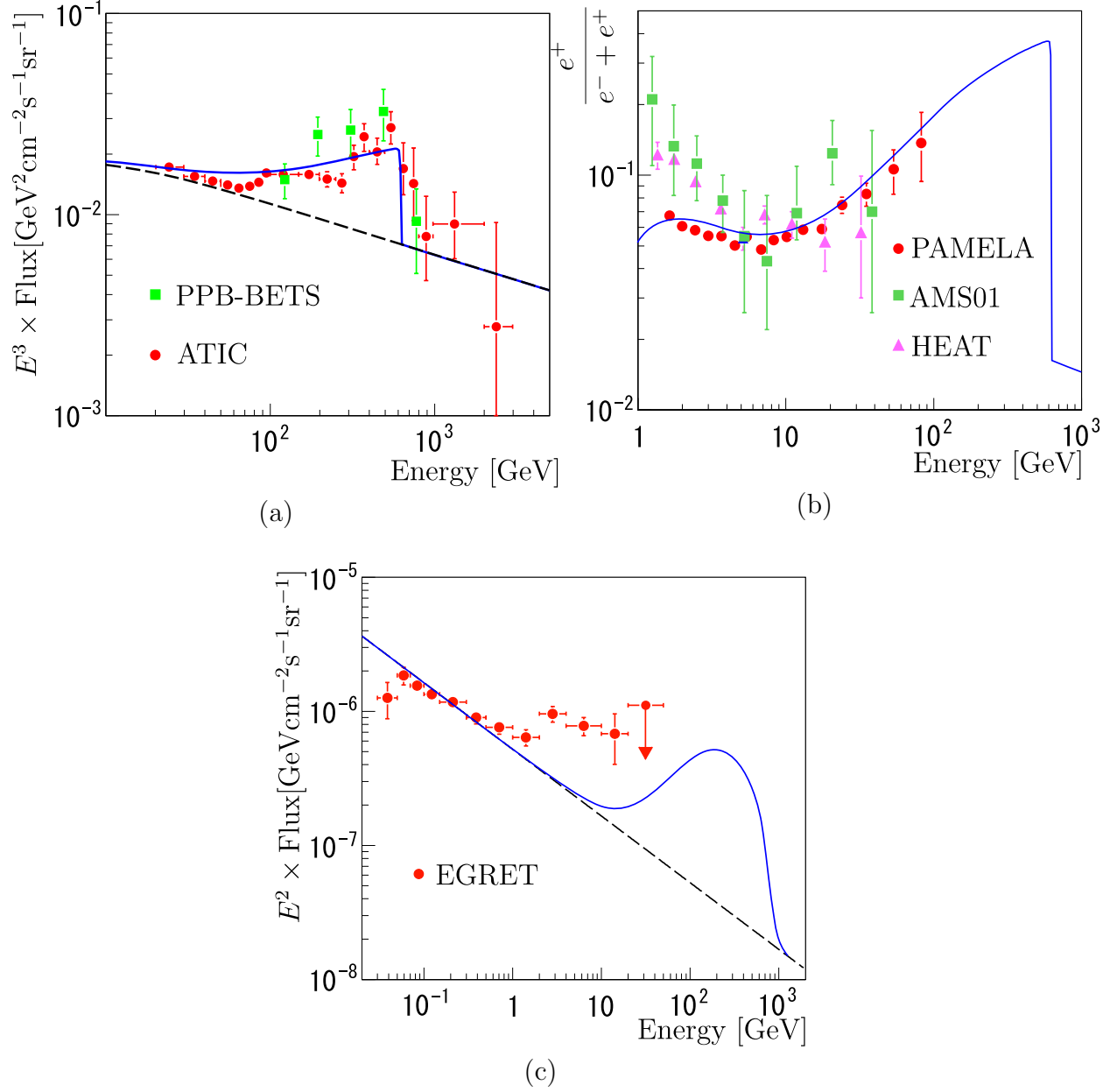


Figure 1: Cosmic ray signals in the present model. (a): positron and electron fluxes with experimental data [4, 21]. (b): positron fraction with experimental data [3, 22, 23]. (c): gamma ray flux with experimental data [24, 25].

degrees of freedom, the gravitino will mainly decay into the SSM sector, and the branching ratio of the the hidden gaugino production is expected to be $O(1)\%$. Therefore, the hidden gaugino can only be a subdominant component of the total DM in this case. Taking account of the presence of the stable neutralino LSP, however, this is not a problem. For instance, for the reheating temperature $T_R \sim 10^6$ GeV, the abundance of the hidden gaugino produced from the gravitino decay is estimated to be $\Omega_\lambda h^2 = 10^{-6} - 10^{-5}$. The hidden gaugino decay can still account for the cosmic-ray anomalies if we adopt a slightly smaller value of $M \sim 10^{15}$ GeV.

With more than two extra spatial dimensions, the SUSY breaking sector may reside on another brane, and the anomaly-mediation may be realized. The presence of light sleptons can then be naturally realized, and the LSP is likely the wino. Due to its large annihilation cross section, the thermal relic abundance of the wino will be much smaller than the observed DM abundance. Then it will become unnecessary to assume the stau neutralino co-annihilation in order to suppress the neutralino LSP abundance, and thus, the slepton masses are not necessarily tied to the LSP mass. As for the production of λ_1 , it is possible that the inflaton decay produces a right amount of λ_1 through either direct or anomaly-induced couplings [30].⁸ Since the gravitino mass can be as heavy as 100 TeV, the gravitino problem is greatly relaxed. The gravitino decay can also produce the hidden gaugino as well as the wino, and the fraction of the λ_1 in the total DM can be as large as $O(1)\%$ in this case, while most of the total DM is the wino non-thermally produced by the gravitino decay.

We have so far assumed that the gauge symmetry in the bulk is $U(1)_{B-L}$, but it is possible to consider another anomaly-free symmetry given by a linear combination of the $U(1)_{B-L}$ and the hypercharge $U(1)_Y$. For instance, if the gauge symmetry in the bulk is identified with a $U(1)_5$, so-called “fiveness” [31], the hidden gaugino is coupled to the higgs and higgsino, in addition to lepton + slepton and quark + squark. However, if the higgsino mass is heavier than m , the hidden gaugino still mainly decays into lepton + slepton, thereby keeping the suppression of the antiproton production.

The decay into a quark pair and the SSM gauginos can actually occur through a

⁸ For the anomaly-induced decay to proceed, we need to introduce hidden matter fields charged under the hidden $U(1)$ gauge symmetry [30].

virtual squark exchange, with a suppressed rate. Compared to the main decay modes into a lepton and slepton pair, the partial decay rate is suppressed by a factor of $O(10^{-3})$ for the squark mass of a few TeV. Such a suppression is small enough to make the DM contribution to the antiproton flux consistent with the observation.

In this paper we have proposed a scenario that a hidden U(1) gaugino constitutes the DM and decays mainly into the leptons through a mixing with a U(1)_{B-L}. We have shown that the energetic leptons from the DM decay can account for the recently reported PAMELA and ATIC anomalies in the cosmic-ray electrons/positrons. We should emphasize that our model is free from an overproduction of antiprotons, if the squarks are heavier than $m \sim 1.3$ TeV. The predicted excess in the diffuse gamma-ray flux around several hundred GeV can be tested by the Fermi satellite.

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